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Original article

Use of a pre-sidedress soil nitrate test (PSNT) to determine nitrogen fertilizer requirements for irrigated corn

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Abstract – In the present study, a 2-year N rate response experiment was conducted in different fields to monitor NO_3-N soil profiles, N accumulation by the crop and final crop performance, in order to assess if soil NO_3-N at pre-sidedressing (Pre-Sidedress Soil Nitrate Test, PSNT) is a reliable indicator for soil N availability for corn in the irrigated area served by canal d'Urgell (Lleida, Spain), and if the test can be used to separate responsive fields from non-responsive fields to sidedress N fertilizer applications. Preliminary soil N availability (N sidedress fertilizer rate + PSNT) critical levels to identify fields that need supplementary N fertilizer applications were established at ca. 300 and 210 kg NO_3-N·ha^{-1}, for $PSNT_{rooting-zone}$ and $PSNT_{0-30\ cm}$, respectively (for a yield goal of 14 t grain·ha^{-1}).

soil nitrate / PSNT / nitrogen / fertilizer rate / corn

Résumé – Utilisation d'un test de nitrate du sol avant l'engrais azoté de couverture (PSNT) pour déterminer les besoins en azote du maïs irrigué. Dans cette étude, une expérimentation de 2 ans sur la réponse au taux d'azote a été conduite dans plusieurs parcelles afin de contrôler les profils de NO_3-N du sol, l'accumulation d'azote dans la culture et la performance finale de la culture ; l'objectif était de vérifier si le NO_3-N du sol avant l'engrais azoté de couverture (PSNT) est un indicateur fiable de la disponibilité en azote du sol pour le maïs dans la zone irriguée par le canal d'Urgell (Lleida, Espagne), et si le test peut être utilisé pour distinguer les parcelles sensibles des parcelles insensibles aux applications d'engrais azotés dans le lit de semence. Les niveaux critiques de disponibilité préliminaire de l'azote du sol (taux d'apport d'engrais azoté dans le lit de semence + PSNT) pour identifier des parcelles qui ont besoin d'applications supplémentaires d'engrais azoté ont été établis à environ 300 et 210 kg NO_3-N·ha^{-1}, pour $PSNT_{zone-racinaire}$ et $PSNT_{0-30\ cm}$ respectivement (pour un rendement escompté de 14 t grains·ha^{-1}).

nitrate du sol / PSNT / azote / dose de fertilisant / maïs

1. INTRODUCTION

The semiarid area served by the Canal d'Urgell is located in the northeastern part of the Ebro Valley (100 km inland from the Mediterranean coast) in Spain, with soils developed on calcilutites, sandstones, and on calcareous alluvial deposits. Corn (*Zea mays* L.) is one of the main crops and accounts for nearly half of the area's nitrogen inputs. Nitrogen fertilizer applications beyond crop requirements result from underestimates of N supplied by the soil and other sources. Soil supply can be of importance in fields with high pre-planting soil mineral N levels, high nitrate content in the irrigation water, and where contributions from net N mineralization may be significant (e.g. soils with high organic matter content or with alfalfa (*Medicago sativa* L.) as the preceding crop).

Accumulation of N in the soil, the presence of shallow water tables in some geomorphological positions during the cropping season, the occurrence of deep percolation due to the concentration of rainfall during fall and winter, and excess irrigation have led to nitrate pollution of surface and subsurface waters in the area. According to Ferrer et al. [9], it is not uncommon to find nitrate contents beyond the maximum permissible concentration of 50 mg $NO_3 \cdot L^{-1}$, established by the EU Nitrates Directive 91/676/EEC. Reducing N fertilizer rates is the first step towards the rationalization of N fertilization practices in the area. Soil nitrate testing has proved to be a good index for assessing soil available N and N

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Table I. Soil characteristics of the Ap horizon and principal site characteristics.

Site	P-1	P-2	P-3	P-4	P-5	P-6
Year	1996	1996	1997	1997	1997	1997
Soil series(1)	Penal	Castellserà	Sarsenit	Castellserà	Sarsenit	Penal
Effective depth(2) (cm)	90	90	60	90	60	90
Previous crop	Corn	Alfalfa	Corn	Corn	Corn	Corn
Water table depth (cm)	80–100	80–100	60–80	80–100	No	80–100
pH (water susp. 1:2.5)	8.3	8.4	8.2	8.3	8.3	8.2
EC (25 °C.E.1:5), $dS \cdot m^{-1}$	0.2	0.18	0.75	0.32	0.2	0.39
Organic matter cont., %	2.4	1.7	2.4	4.1	2.7	2.8
Equiv. calcium carb., %	37	39	15	45	13	35
Olsen P, ppm	23	12	13	29	53	20
K (amonium Ac.), ppm	240	197	146	303	421	365
Mg (amonium Ac.), ppm	425	400	> 600	467	189	384
Coarse materials (% vol)	NO	NO	10	NO	10	NO
Sand, %	13.7	11.9	38	8.7	47.2	13.2
Silt, %	52.1	57.1	34.7	48.2	31.1	53.8
Clay, %	34.2	31	27.3	43.1	21.7	33
Texture class	Si-C-L	Si-C-L	C-L	Si-C	L	Si-C-L

(1) According to Herrero et al. [13]; (2) Rooting depth defined by the presence in the bottom of the horizon of a clay layer or a paralitic contact.

fertilizer rate recommendations for corn, under different combinations of soils, climatic conditions and management practices [3, 6, 21, 26]. A previous on-farm study carried out in the area [24] could not find clear relationships between soil NO_3-N at pre-planting (early-spring), N fertilizer rate, plant N uptake and final crop performance. Instead, according to Magdoff [18] and Lory et al. [17], by sampling the surface 30 cm of the soil at pre-sidedressing (Pre-sidress Soil Nitrate Test, PSNT), to coincide with the onset of the active N uptake period (around crop stage V6), the test was likely to reflect the mineral N remaining from the previous season as well as the variations due to net N mineralization and NO_3-N redistribution within the profile before the crop's most active N uptake period.

The same authors suggested that the PSNT could be used to define a critical value above which no yield response to sidedress N fertilizer applications would be expected. In this way, the decision of whether a cornfield needs N fertilizer applications at sidedressing could be based on the PSNT.

In the present study, a 2-year N rate response experiment was conducted in different fields to monitor NO_3-N soil profiles, N accumulation by the crop and final crop performance. These data were used to: (i) assess if soil NO_3-N at pre-sidedressing (PSNT) is a reliable indicator for soil N availability for corn in the prevailing conditions of the study area, and (ii) determine if the $PSNT_{0–30\ cm}$ is able to separate responsive fields from non-responsive fields to top dressing N fertilizer applications.

2. MATERIALS AND METHODS

A total of six N fertilizer response trials with corn were conducted in farmers' fields in 1996 and 1997. These fields were located in the irrigated area of the R. Urgell's catchment. The climate in the area is considered to be typical continental Mediterranean, with dry and warm summers and cold winters [24]. Site locations in 1996 (P-1 and P-2) were not repeated in 1997 (P-3 to P-6). Soils at P-1 and P-6 were classified as Fluventic Haploxerepts (Fulvic Cambisol, FAO 1998), fine-loamy, mixed and mesic, P-2 and P-3 as Gypsic Haploxerepts (Haplic Gypsisol, FAO 1998), fine-loamy, mixed and mesic, and P-3 and P-5 as Xeric Haplocalcids (Calcisol, FAO 1998), loamy-skeletal, carbonatic and mesic [22]. Table I shows the soil characteristics at each site. The sites had similar management histories, with no manure applications in the previous year, and with corn as the previous crop (except for site P-2 that had alfalfa). The cultivar *Pioneer Juanita* was used in all sites but one (P-4) where *Pioneer Elionora*, a cultivar with similar growth characteristics, was grown. Planting was around the usual dates practiced in the area (end of March to beginning of May), with harvest dates beginning by the end of September. Water was applied by surface irrigation at a dose of ca. 100 mm per event, scheduled at fixed 10- to 14-day intervals, starting in mid-March and ending in mid-September.

The treatments (N_0, N_1, N_2 and N_3) consisted of four sidedress N fertilizer rates (0, 100, 200 and 300 $kg \cdot ha^{-1}$), with three replications except for sites P-5 and P-6, that had only two. Individual plot size was 3.5 × 14 m, arranged in a complete random design in all sites. Urea was applied by hand within the rows and incorporated into the soil when the corn plants were 5 to 20 cm tall (V1 to V4 stage), Hanway [12], approximately within 20 to 35 days after planting (see Tab. II). Plant populations ranged from 70 000 to 75 000 $plants \cdot m^{-2}$ with a row separation of 70 cm. Except for the application of the N fertilizer treatments, the rest of the management practices were carried out by the farmer. In 1996 (P-1 and P-2), the farmers did not apply N at pre-planting, while in 1997 (P-3 to P-6) 100 kg $N \cdot ha^{-1}$ were applied to each field before planting and before the first soil sampling date (early spring) (Tab. II).

Table II. Selected management practices and PPNT and PSNT sampling dates.

Site	P-1	P-2	P-3	P-4	P-5	P-6
Year	(1996)	(1996)	(1997)	(1997)	(1997)	(1997)
Date of seeding	22-4 (112)	2-5 (122)	28-3 (87)	13-4 (103)	28-3 (87)	13-4 (103)
Date of silking	19-7 (200)	25-7 (206)	2-7 (183)	18-7 (199)	2-7 (183)	18-7 (199)
Date of harvest	12-10 (285)	15-10 (288)	23-9 (266)	25-9 (268)	23-9 (266)	25-9 (268)
Previous crop	corn	alfalfa	corn	corn	corn	corn
Pre-planting fert.						
Date of application	19-4 (109)	19-4 (109)	18-3 (77)	1-4 (91)	18-3 (77)	1-4 (91)
Type of fertilizer	Blending	Blending	Blending	Blending	Blending	Blending
Manure application	NO	NO	NO	NO	NO	NO
N rate (kg N·ha^{-1})	0	0	100	100	100	100
Sidedress. fert.						
Date of application	24-5 (144)	24-5 (144)	2-5 (122)	2-5 (122)	9-5 (129)	2-5 (122)
Phenological stage	4V	2V	2V	1V	3V	1V
Type of fertilizer	Urea	Urea	Urea	Urea	Urea	Urea
Early spring NT(1)						
Date of sampling	25-4 (115)	25-4 (115)	5-5 (125)	5-5 (125)	5-5 (125)	5-5 (125)
Phenological stage	pre-emerg.	pre-emerg.	2V	1V	2V	1V
Pre-planting irrigation	7-4 (97)	9-4 (99)	25-4 (115)	2-4 (92)	none	none
Acc. precip(2) (mm)	26	26	35	35	35	35
PSNT					26-5 (146)	
Date of sampling	30-5 (150)	30-5 (150)	22-5 (142)	26-5 (146)	5V	26-5 (146)
Phenological stage	4V	3V	5V	4V	none	4V
Pre-sidedress. irrig.	none	none	none	none	20	none
Acc. precip(3) (mm)	34	34	17	20		20

(1) Early Spring Nitrate Test; (2) accumulated precipitation during the 10 days previous to the Early Spring NT (in P-1 and P-2) or between pre-planting fertilizer application and Early Spring NT (P-3 to P-6); (3) accumulated precipitation between the PPNT and the PSNT. * Dates in parentheses indicate Day of the Year (DOY).

In sites P-1, P-2, P-3 and P-4, soil samples were collected throughout the growing season on each individual plot at depths of 0–30, 30–60 and 60–90 cm to determine soil NO_3-N and moisture content. Sites P-5 and P-6 were only sampled in early spring, PSNT and for residual NO_3-N (at harvest). For each individual plot, a 5-core composited sample was taken from the surface layer (0–30 cm). For deeper layers, only 2 cores per sample were taken, following Onken et al. [19]. In early spring (Tab. II), one composite sample per field was taken, just before the experimental plots were positioned in the cornfield. All samples were kept cooled until they were air-dried and sieved (2 mm). The soil extract from a 1:2 soil-water solution was determined colorimetrically for NO_3-N with a Technitron Autoanalyzer (Anasol, ICA Instruments, France) within 24 hours after sampling. Determination of soil mineral N as ammonium was not considered of relevance as suggested by Villar et al. [24]. In addition, when using the PSNT as an index for soil N availability and N fertilizer requirements, the estimation of the mineral soil N only takes into account the nitrate form (N-NO_3), Magdoff [18], Andraski and Bundy [1]. Nitrate concentrations (mg $NO_3 \cdot L^{-1}$) obtained from the analyses were converted to NO_3-N content at each 30 cm-layer (kg NO_3-N·ha^{-1}), considering values of bulk density and volume content of coarse materials estimated from field observations. Bulk densities ranged from 1.40 to 1.45 Mg·m^{-3}.

Biomass accumulation in the grain, stover, ear blade, stalk and leaves were monitored during the growing season until physiological maturity, by collecting the plants from a 2-row × 1.8 m sample (2.8 m^2), in each individual plot. Throughout the growing season, five samples were taken at P-1 and P-2 and four samples at P-3 and P-4. Sites P-5 and P-6 were only sampled around the V4 stage and at harvest. Sufficient discard area was left between sampling areas to prevent edge effects. Partitioned fresh weight was determined in the field and a sub-sample from each partition was removed for moisture determination in the laboratory (oven-dried at 65 °C). Dried sub-samples were ground to determine total N content with the Kjeldahl method, and plant N accumulation was obtained by summing up the result of multiplying dry weight by N concentration of each part of the plant. Grain yields are expressed at 14% moisture content.

Additional crop N use indices were calculated to compare N uptake, plant N accumulation and crop performance between treatments. Recovery of fertilizer N by the crop (NREC) for each sidedress fertilizer level was calculated as described by Greenwood and Draycott [11]. In addition, three N use efficiencies were calculated for each treatment: Nitrogen Use Efficiency (NUE_1, kg grain yield per kg fertilizer N applied), Nitrogen Uptake Efficiency (NUE_2, kg of N

uptake per kg of applied fertilizer) and Nitrogen Utilization Efficiency (NUE_3, kg of grain per kg of N uptake).

3. DATA ANALYSIS

For statistical purposes, the experimental site was taken as the main factor, considering only the sites where three replications per treatment were implemented (P-1, P-2, P-3 and P-4). Data from sites P5 and P-6 were used only in the observational and graphical analyses. When interpreting the results, the influence of the site was considered to be the combined effect of crop season, soil type and management practices at each experimental site. The secondary factor in the analysis was the N fertilizer rate applied at sidedressing.

An ANOVA analysis was run on grain yield, total biomass and plant N content, among other variables of interest. Mean separation was performed by the Student-Newman Keuls Test [20]. Although the N levels were quantitative, for the purpose of mean separation tests they were considered as discrete levels. All statistical tests were performed with the SAS program [20].

To support the statistical analysis aimed at comparing differences between sites and treatments, overall data were used to calculate crop N use indices and to perform observational and graphical analyses to help to define possible trends, preliminary critical levels or interactions between measured variables of interest.

4. RESULTS AND DISCUSSION

The months prior to planting were unusually wet for both seasons, with winter (November to January) accumulated precipitation of 240 and 230 mm in 1996 and 1997, respectively (Tab. III). During both years, there was scarcely any precipitation during February and March. Summer precipitation was above the average in 1997, while in 1996, the growing season received less precipitation than normal, except for the latter period. Air temperatures were slightly higher in 1997 than in 1996. In 1996, temperatures during June and July were warmer than usual, but colder than the average in September and October (Tab. III). A warm spring (from February to May) and a cold summer characterized the growing season in 1997. Priestley-Taylor accumulated Potential Evapotranspiration (ETp) during the growing season was ca. 850 mm in 1996 and 750 mm in 1997. In 1997, due to earlier sowing, the silking stage in sites P-3 and P-5 occurred substantially earlier than in the remaining sites (Tab. II).

4.1. Soil NO_3-N, plant N uptake and grain yield

Soil NO_3-N content of the entire root zone in early spring (Tab. III) ranged from 90 to 332 kg $N \cdot ha^{-1}$ (0–60 or 0–90 cm depending on the effective depth at each site, see Tab. I).

Figure 1 shows the variation in the soil profile NO_3-N content for the most fertilized treatment (N_3, 300 kg $N \cdot ha^{-1}$) and four sites. A layer of gravel (paralithic contact) at 60 cm limited soil depth at site P-3, and therefore the graphs only display NO_3-N content at 0–30 and 30–60 cm. As can be observed, seasonal patterns were similar among the sites. Overall, three phases could be recognized:

(1) the initial phase, corresponding to the period between early spring (pre-emergence to the 2V stage, late April to early May) and shortly after sidedressing fertilizer application (mid-April to mid-June, DOY 105 to 166). This period was characterized by a general accumulation of NO_3-N in the surface horizon, due to the contribution from N mineralization as the soil temperature increases in spring and the application of sidedress N fertilizer (300 $kg \cdot ha^{-1}$). This was also observed by Villar et al. [24]. Table IV shows that for the non-fertilized treatment (N_0) the accumulation of NO_3-N in the topsoil layer was especially apparent at sites

Table III. Monthly mean average temperature and accumulated precipitation in Palau d'Anglesola.

	Monthly mean avg. temperature (°C)			Monthly mean acc. precipitation (mm)		
Month	1996	1997	Long-term avg.	1996	1997	Long-term avg.
Jan.	8.2	6.5	5.1	118.8	91.1	32.9
Feb.	5.7	7.9	6.8	5.7	0.0	12.1
March	9.4	10.7	10	11.1	0.0	17.9
April	12.7	13.3	12.2	48.5	33.2	28.9
May	16.4	17.3	16.7	30.6	24.5	47.7
June	20.8	20.2	20.2	52.0	81.7	41.5
July	22.8	22.1	23.6	9.6	39.6	13.8
Aug.	22.6	23.7	23.7	27.3	92.4	33.2
Sept.	17.1	20.4	19.2	23.2	25.5	48.7
Oct.	13.7	11.5	13.7	33.6	15.3	47.7
Nov.	8.7	9.4	8.9	82.3	32.2	48.2
Dec.	7.4	5.9	5.9	54.0	77.0	27.0
TOTAL				496.7	512.5	399.6

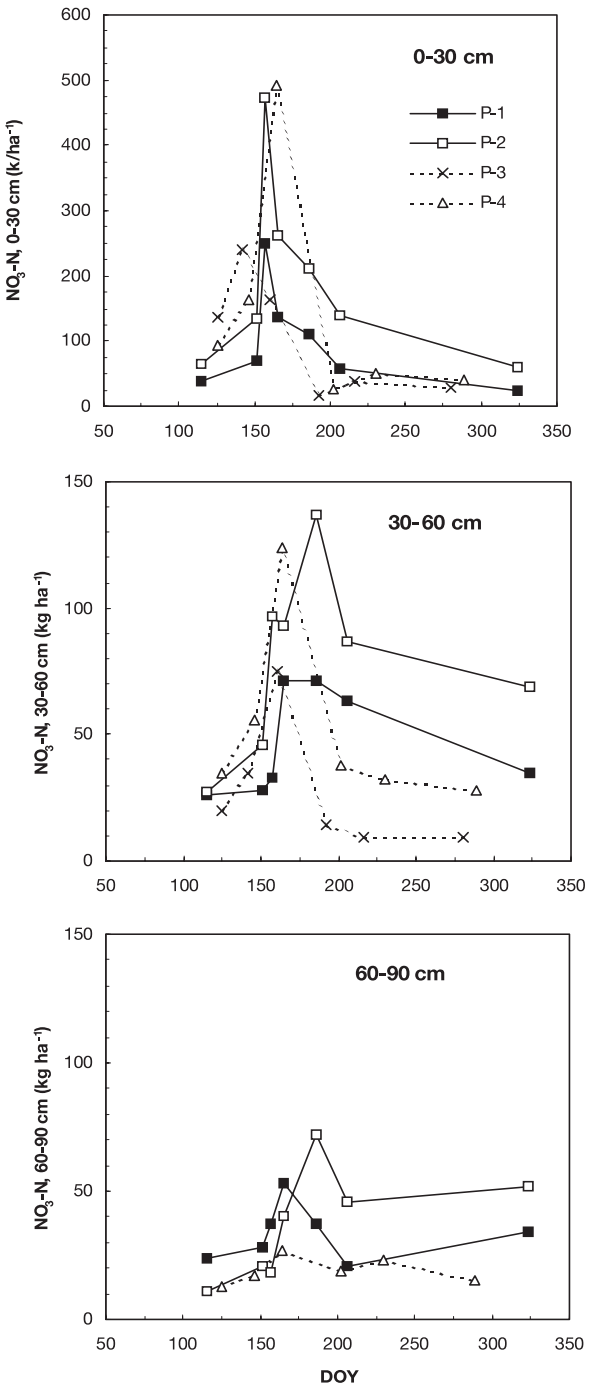

Figure 1. Temporal evolution of soil NO_3-N distribution within the profile for the highest N sidedress N fertilizer treatment, N_3 (300 kg·ha^{-1}). Soil NO_3-N values correspond to the average values at each site.

P-2 and P-4. The reason behind this could be the higher contribution from N mineralization due to the presence of alfalfa as the preceding crop and high organic matter content, respectively. In all sites, some NO_3-N accumulation was observed in the 30–60 cm horizon, probably transported by the infiltration of water from rainfall (Tab. III), considering that the soil profile was relatively wet at planting time. However, during this period, drainage below the rooting depth and subsequent N loss through leaching is not likely to occur if the farmer does not irrigate. To support this hypothesis, the CropSyst Suite Simulation Model [23] was calibrated and validated for corn for the prevalent conditions in the area [8], and soil water and N balance, crop development and crop growth were simulated at each experimental site (data not shown). The simulation results showed that between planting and PSNT there was no drainage below the rooting depth in all sites;

(2) this period (mid-June to end of July, DOY 166 to 212) could be associated with the crop active growth and main N uptake period (see Fig. 2). This active uptake by the crop was reflected by a sharp reduction in NO_3-N content in the surface and subsurface horizons. This decrease in NO_3-N in the soil surface was also the result of NO_3-N transport to deeper horizons due to the intensification of the irrigation events during this period, as NO_3-N accumulated in the subsurface layers (30–60 and 60–90 cm). The decrease in soil NO_3-N in the subsurface horizons before grain filling could be attributed either to crop N absorption by deeper roots or to N transport to deeper horizons. The uncommonly high values of precipitation (Tab. III) registered in summer 1997 (June + July) were also reflected by lower NO_3-N contents in the 30–60 cm horizon after flowering at sites P-3 and P-4, compared with P-1 and P-2 in 1996. The combined effect of irrigation and the abundant rainfall during summer 1997 possibly moved the sidedress N fertilizer to depths below 60 and 90 cm. This hypothesis is supported by Villar et al. [24] who observed, in similar field conditions, that there was a downward movement of N in the soil profile and an eventual N loss through leaching, due to irrigation. The same authors calculated a simple N balance and concluded that there was some soil unaccounted N that eventually may be lost through leaching. In addition, simulation results with the CropSyst Suite Model confirmed that, on average, soil water drainage (from seeding to harvest, rooting depth) was greater in 1997 than in 1996 (208 mm vs. 398 mm, respectively). The observed sub-surface NO_3-N enrichment, in comparison with surface NO_3-N depletion, was proportionally more significant in site P-3 than in the others, possibly due to the coarser texture of the soil. This hypothesis was corroborated by higher simulated soil water drainage in site P-3 (from seeding to harvest, rooting depth), in comparison with the average drainage value in the remaining 1997 sites (429 mm vs. 381 mm);

(3) this period (end of July to October-November, DOY 212 to 290-320) was characterized by the reduction in the N uptake rate and fewer irrigation events. In 1996 (P-1 and P-2), post-harvest sampling was conducted as late as late November. Due to the abundant precipitation that fell during that autumn, some NO_3-N from the surface horizons (0–30 and 30–60 cm) could have been moved deeper (60–90 cm) and below the rooting depth. The rooting zone residual NO_3-N content at the end of the growing season fluctuated between 33 and 181 kg N·ha^{-1} for the effective depth. Finally, the higher NO_3-N contents that were found in site P-2 at harvest clearly reflected the contribution from

Table IV. Soil NO_3-N content (kg NO_3-N·ha^{-1}) in the profile taken in Early Spring and pre-sidedressing, for the non-fertilized treatment (N_0).

Depth (cm)	P-1	P-2	P-3	P-4	P-5	P-6
Early spring						
0–30	39	64	138	94	287	56
30–60	26	27	20	35	45	33
60–90	24	11	-	13	-	14
Root zone	89	91	158	142	332	103
PSNT						
0–30	69a	135ab	146ab	104ab	206	53
30–60	28a	46a	24a	69a	70	48
60–90	28a	21a	-	19a	-	23
Root zone	125a	181a	170a	192a	276	124

* Among columns, means followed by the same letter are not significantly different at the 0.005 significance level. ** No statistical analysis was conducted with the Early Spring sampling due to lack of true repetitions. *** Data from sites P-5 and P-6 were not included in the statistical analysis because they were only taken for observational and graphical analysis purposes.

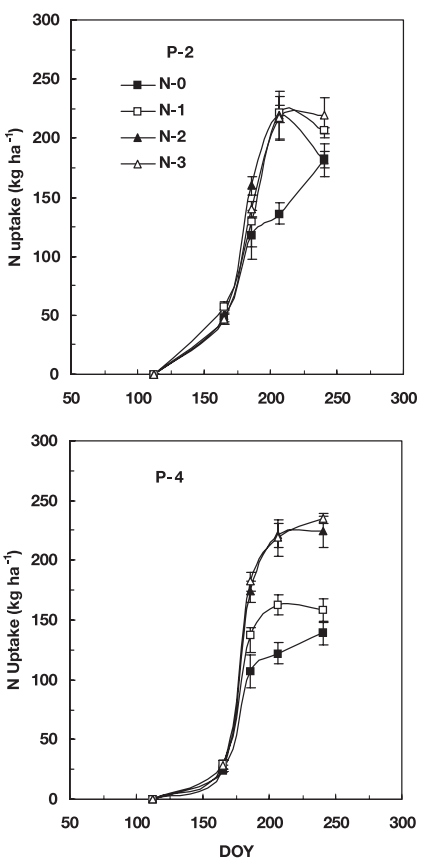

Figure 2. Aboveground N uptake accumulation by corn for the P-2 (1996) and P-4 (1997) sites. Error bars correspond to standard error values.

N mineralization of the incorporated alfalfa stand. As shown in Figure 1, part of this N was redistributed and accumulated in deeper horizons.

In general, N uptake by the crop followed the same trend for the four sites that were examined (the accumulation patterns were similar for all sites, and therefore only data for P-2 and P-4 sites are shown). Figure 2 shows slow initial N uptake due to small N demand by the crop during this period, with uptake rates ranging from 0.44 to 0.86 kg N·ha^{-1}·day^{-1}, depending on the site and N fertilizer treatment. Following the V6 stage and initiation of stem elongation (coinciding approximately with first biomass sampling, between 150 and 160 DOY), N uptake became more intense, reaching peak rates of ca. 2.5 to 4.1 kg N·ha^{-1}·day^{-1} for the highest N fertilizer treatments. These rates were in accordance with values reported by Magdoff [18], Jokela and Randall [14] and Karlen et al. [15], who found maximum uptake rates 2 to 3 weeks prior to silking. For the highest N fertilizer treatments, 64 to 81% of total N uptake was accumulated by silking. This period of maximum N uptake that began around the V6 stage (mid-June, DOY 160) continued until the beginning of grain filling (end of July, approximately DOY 210), coinciding with the blister stage at the majority of sites. Throughout the grain-filling period, N uptake rates were much lower than during active vegetative growth and pollination. Except for site P-2, that had alfalfa as the previous crop, clear differences were observed between the N_0 treatment (no sidedress N fertilizer) and the fertilized treatments (Fig. 2 and Tab. V). For N_0, N uptake accumulation seemed restricted shortly after active growth was initiated.

Selected final crop performance variables are displayed in Table V. The overall grain yield average was 14.3 t·ha^{-1}, with a minimum observed value of 9.9 and a maximum of 17.3 t·ha^{-1}. Accumulated biomass at harvest was 23.6 t·ha^{-1}, on average, ranging between 17.4 and 28.4 t·ha^{-1}. Poor crop performance was observed for the N_0 plots (except for site P-2) due to N shortage in the soil, as noted earlier.

4.2. The Pre-sidedress Soil Nitrate Test (PSNT) as an index of soil N availability

Figure 3 shows the combined relationship between soil available N in the rooting zone before the active N uptake period (sidedress N fertilizer rate + soil mineral N content in the rooting zone at pre-sidedressing), residual NO_3-N (rooting

Table V. N uptake, grain yield, biomass, recovery of fertilizer N (NREC) and nitrogen use efficiencies NEU_1, NUE_2 and NUE_3, for the N rate treatments.

Site	Plant N uptake ($kg \cdot ha^{-1}$)	Grain N uptake ($kg \cdot ha^{-1}$)	Biomass ($t \cdot ha^{-1}$)	Grain yield ($t \cdot ha^{-1}$)	NREC ($kg \cdot kg^{-1}$)	NUE_1 ($kg \cdot kg^{-1}$)	NUE_2 ($kg \cdot kg^{-1}$)	NUE_3 ($kg \cdot kg^{-1}$)
P-1								
N_0	191a	117a	22.8a	12.0a	-	-	-	63
N_1	267b	190b	25.3a	15.8b	0.76	158	2.67	59
N_2	261b	188b	28.2a	17.3b	0.35	87	1.31	66
N_3	256b	175b	26.2a	15.4b	0.22	51	0.85	60
P-2								
N_0	275a	166a	28.4a	14.3a	-	-	-	52
N_1	260a	177a	26.6a	15.0a	-0.15	150	2.60	58
N_2	282a	196a	24.0a	15.7a	0.04	78	1.41	56
N_3	261a	169a	25.7a	14.1a	-0.05	47	0.87	54
P-3								
N_0	175a	123a	24.0a	12.7a	-	-	-	72
N_1	217a	168a	22.3a	14.8a	0.42	148	2.17	68
N_2	200a	152a	23.2a	14.6a	0.13	73	1,00	73
N_3	219a	170a	23.5a	15.0a	0.15	50	0.73	69
P-4								
N_0	139a	101a	19.4a	10.7a	-	-	-	77
N_1	158a	119a	20.4a	12.1a	0.19	121	1.58	77
N_2	224b	177b	23.1b	14.5b	0.43	73	1.12	65
N_3	235b	187b	24.1b	15.5b	0.32	52	0.78	66
P-5*								
N_0	148	111	19.8	12.5	-	-	-	85
N_1	183	146	22.1	14.5	0.35	145	1.83	79
N_2	222	169	25.6	15.7	0.37	78	1.11	71
N_3	224	173	25.0	16.9	0.25	56	0.75	75
P-6*								
N_0	117	84	17.4	9.9	-	-	-	85
N_1	173	130	20.0	13.5	0.56	135	1.73	78
N_2	211	162	23.0	15.4	0.47	77	1.06	73
N_3	234	176	24.4	15.9	0.39	53	0.78	68

* These experiments consisted only of two repetitions and, therefore, no statistical analysis was performed. ** Within columns, means followed by the same letter are not significantly different at the 0.05 significance level. NREC: Recovery of fertilizer N by the crop, as Greenwood and Draycott (1988). NUE_1: Nitrogen Use Efficiency (kg of grain yield per kg of applied fertilizer), NUE_2: Nitrogen Uptake Efficiency (kg of N uptake per kg of applied fertilizer), NUE_3: Nitrogen Utilization Efficiency (kg of grain yield per kg of N uptake).

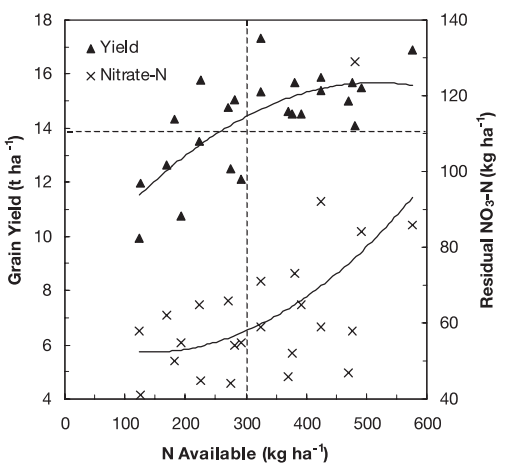

Figure 3. Observed relationships between yield, residual NO_3-N and available N at sidedressing (sidedress N fertilizer + $PSNT_{rooting-zone}$). All sites considered.

zone) and yield. Using the Cate-Nelson graphical procedure [4], an inflection point at approximately 300 kg $N \cdot ha^{-1}$ could be identified. For levels of available N at sidedressing beyond this point no yield differences were found, and as a consequence N started accumulating in the profile. The data points in the upper-left square correspond to the control treatment (N_0) in 1996. In this case, mineralization from a preceding alfalfa stand and lower N losses through leaching resulted in a satisfactory yield despite lower soil N available levels before active growth. This lack of response to N fertilizer following alfalfa agrees with data from field experiments with corn grown in Wisconsin (USA), Andraski and Bundy [1].

Figure 4 shows the relationship between grain yield, N content in the grain, plant uptake and available N at sidedressing (sidedress N fertilizer + $PSNT_{rooting-zone}$). These graphs show that when N fertilization resulted in a level of soil N availability above a critical value, excess N was accumulated by the crop without any apparent yield increase. Using the Cate-Nelson procedure in Figure 4a, a critical N content in the grain

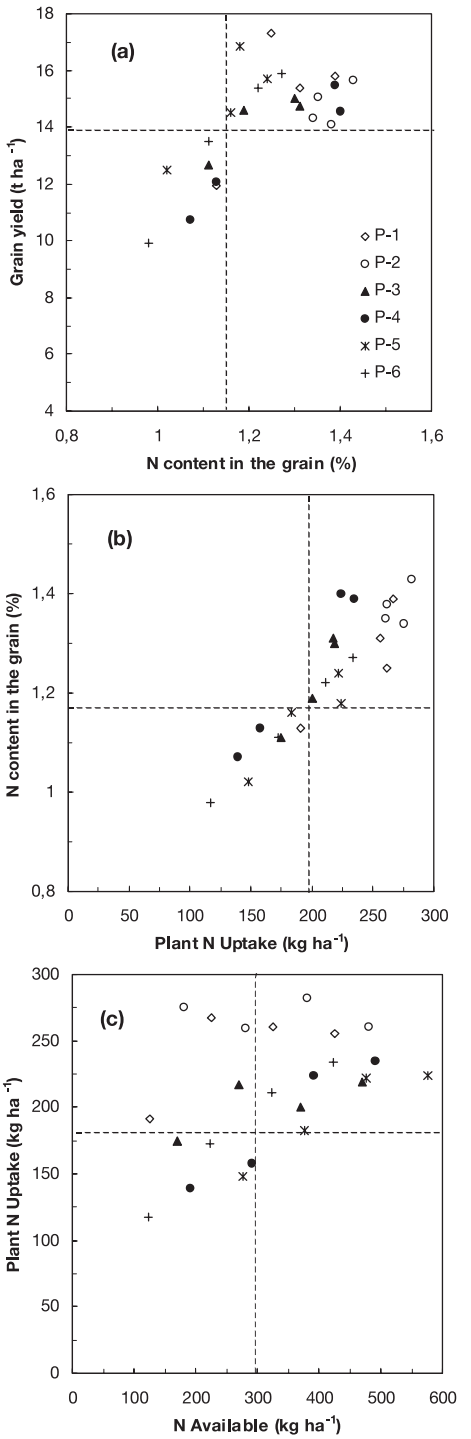

Figure 4. Observed relationships between: (a) N content in the grain and yield; (b) plant N uptake and N content in the grain; and (c) available N at sidedressing (sidedress N fertilizer + $PSNT_{rooting-zone}$), for all the plots.

between 1.1 and 1.2 kg N·100 kg^{-1} grain could be suggested. This critical level for N content in the grain agrees with the value of 1.2 kg N·100 kg^{-1} reported by Villar et al. [24]. Figure 4b indicates that, to reach N concentrations in the grain above this critical level and to ensure a non-N-limited potential yield (above 14 t·ha^{-1}), the crop needed to accumulate a minimum of 200 kg N·ha^{-1}. Plant N uptake depends on N crop demand (crop growth) and N availability in the soil. The relationship between plant N uptake and available N at sidedressing was plotted (Fig. 4c), and the Cate-Nelson procedure used to define a critical level. For a plant N uptake level of around 200 kg N·ha^{-1}, a critical level of 300 kg N·ha^{-1} (sidedress N fertilizer + $PSNT_{rooting-zone}$) was defined. To reaffirm the existence of such a luxury consumption of N by the crop, some N efficiency indices were calculated (Tab. III). There was a clear decrease in the Nitrogen Recovery Fraction (NREC) as the N rate increased, with an average value of 0.39 (Tab. III). These data suggested that lowering the N fertilizer rate to a certain limit enhanced apparent substitution of N fertilizer by N supplied by the soil, without detrimental consequences for crop growth and N uptake. Nitrogen Utilization Efficiency (NUE_3) was quite constant among treatments and sites, with an average value of 69 (kg grain·kg^{-1} N uptake), but showing consistently lower values for the higher N rate treatments. Nitrogen Uptake Efficiency (NUE_2) showed consistently lower values for the higher N rate treatments, with an average factor of 2.10 for N_1 and 0.79 for N_3 (kg uptake·kg^{-1} applied N). The relatively constant values of NUE_3 and the decrease in NUE_1 suggest again that excess N applications in these conditions increase the proportion of N that is not absorbed by the crop during the growing season, and therefore the possibilities of N loss.

The critical soil N available sufficiency levels at sidedressing found in this study may need some readjustment in years when irrigation may be restricted occasionally during the growing season and water shortages may occur. The occurrence of drought during the growing season may be more important in explaining N uptake and grain yield differences than soil nitrate N contents [24].

4.3. The Pre-sidedress Soil Nitrate Test ($PSNT_{0-30\ cm}$) as a N fertilizer recommendation tool

The need for deep sampling is a critical restrictive aspect for a wider use of PSNT tests in commercial fields. A strong relationship between $PSNT_{rooting-zone}$ and $PSNT_{0-30\ cm}$ may indicate that sampling at a shallower depth may still provide a valid estimation of soil mineral N at sidedressing, and thus be used for recommendation purposes. In the present study, prediction of 30–60 and 60–90 cm NO_3-N contents from 0–30 cm sampling was unreliable (linear regression correlation not shown). Ehrhardt and Bundy [7] and Brown et al. [2] also observed a lack of correlation between NO_3-N content in the surface and subsurface layers. This indicates that NO_3-N distribution within the soil profile is not regular in relation to variability factors such as the previous crop, soil characteristics and manure history, early spring irrigation and winter and early spring rainfall, among others. However, it is interesting to note that NO_3-N content from 0–30 cm represented a significant fraction of the total NO_3-N content in the profile, suggesting that shallow samples (0–30 cm) could provide a reasonable estimation of soil available N for corn. Taking all the sites together, NO_3-N content in the upper layer

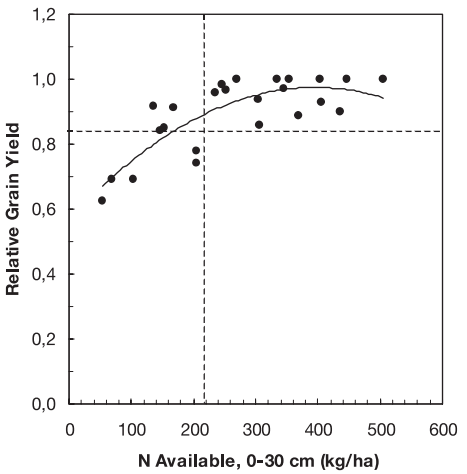

Figure 5. Observed relationship between relative yield and available N at sidedressing in the surface layer (sidedress N fertilizer + $PSNT_{0–30\ cm}$).

represented from 43 to 75% of NO_3-N (0–90 cm), and from 52 to 86% NO_3-N (0–60 cm).

Even though the $PSNT_{0–30\ cm}$ does not account for all the soil NO_3-N accumulated below the upper 30 cm of the soil and, therefore, may not entirely represent the mineral N available for the crop before sidedress N fertilizer is applied, the test may be a reliable tool to separate responsive from non-responsive fields to N fertilizer applications. Figure 5 shows the relationship between soil available N in the upper 30 cm of the soil at sidedressing (sidedress N fertilizer + $PSNT_{0–30\ cm}$) and relative yield. Relative yield for each field was calculated as the ratio between the average yield for each treatment and the maximum yield for that field. Applying the Cate-Nelson method, a critical level of available N (0–30 cm) of ca. 210 kg $N \cdot ha^{-1}$ could be assumed. Beyond this point, grain yield would remain above 82% relative to the maximum yield obtained in each particular field.

By measuring on-site $PSNT_{0–30\ cm}$ in a field, between planting and sidedressing, a $PSNT_{0–30\ cm}$ value above 210 kg NO_3-$N \cdot ha^{-1}$ (45 mg NO_3-$N \cdot kg^{-1}$) for a yield goal of 14 t grain$\cdot ha^{-1}$ would indicate that there is no need for supplemental N fertilizer applications. For $PSNT_{0–30\ cm}$ values below the critical level, sidedress N fertilizer should be applied, at a minimum rate of (210 – $PSNT_{0–30cm}$), in order to achieve near maximum yields (around 14 $t \cdot ha^{-1}$). In similar conditions, but for lower yield expectations (yield goal of 10 t grain$\cdot ha^{-1}$), Villar et al. [25] found that a $PSNT_{0–30\ cm}$ level between 94 and 142 kg $N \cdot ha^{-1}$ (21 to 32 mg NO_3-$N \cdot kg^{-1}$) was required. These values are also in concordance with the $PSNT_{0–30\ cm}$ levels found by other researchers [10, 16, 27]. The results from site P-2 suggest that, after alfalfa, corn does not need supplemental N fertilizer applications in this region, regardless of the soil nitrate levels found at sidedressing. This agrees with observations by Dou et al. [5]. More response trials would be necessary to narrow this preliminary interval and to separate responsive from non-responsive sites better.

5. CONCLUSIONS

The monitoring of NO_3-N soil profiles and N accumulation by the crop showed that, by carrying out the PSNT before the onset of the period of intensive irrigation (between the end of May and mid-June), the soil N that is likely to be available for the crop before the period of maximum N uptake could be predicted. The PSNT reflected the N contribution from mineralization and some nitrate redistribution to deeper layers in the profile. Abundant irrigation after the application of sidedress N fertilizer led to the downward transport of non-absorbed NO_3-N by the crop, from the surface layer to deeper layers and eventually below the rooting depth. This was especially evident in the sites with coarser soil textures, due to a greater water drainage below the rooting depth.

Preliminary sufficiency levels to identify N excess situations could be established for sidedress soil N availability (N fertilizer rate + soil mineral N content in the rooting zone at pre-sidedressing), and N content in the grain. For a yield goal of 14 t grain$\cdot ha^{-1}$, a critical level of N content in the grain of 1.2 kg $N \cdot 100\ kg^{-1}$ was identified. This required a minimum of 300 kg $N \cdot ha^{-1}$ of available N in the soil (sidedress N fertilizer + $PSNT_{rooting–zone}$). For sidedress N fertilization applications that resulted in a level of soil available N beyond this level, unaccounted N excess in the soil was either absorbed by the crop without any crop response, was accumulated in the soil at the end of the growing season, or was lost through leaching.

The soil nitrate content of the surface horizon (0–30 cm) sampled at pre-sidedressing did not correlate well with N content deeper in the soil (30–60 cm and 60–90 cm). However, $PSNT_{0–30\ cm}$ could be used to identify fields that need supplementary N fertilizer applications. A preliminary critical level of $PSNT_{0–30\ cm}$ of around 210 kg NO_3-$N \cdot ha^{-1}$ (45 mg NO_3-$N \cdot kg^{-1}$) was established for near maximum grain yield (approximately, about 14 $t \cdot ha^{-1}$).

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